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MECHANICAL PROPERTIES AND MICROSTRUCTURE OF PM Mn-Cr-Mo STEELS WITH LOW CARBON CONCENTRATION

The effect of chemical composition of the sintering atmosphere on the microstructure and mechanical properties of PM structural low-carbon steels is presented. The base powders were Astaloy CrL, Astaloy CrM, low carbon ferromanganese and graphite C-UF. From the base powders two mixtures with compositions of Fe-3%Mn-(1.5/3%)Cr-(0.2/0.5)%Mo-0.2%C were prepared. Following pressing in a steel rigid die, compacts were sintered at 1250°C for 60 min in a semi-closed container. 5%H2-95%N_2 mixture and air were the sintering atmospheres. For sintering in air, lumps of ferromanganese were placed with the compacts in the container. After sintering, half of the samples were tempered at 200°C for 60 minutes in air. Mechanical tests (tensile, bend, toughness, hardness) and microstructural investigations were performed.

The microstructures of the steels were inhomogeneous, mainly ferritic-bainic. Tempering of steel based on Astaloy CrM sintered in an atmosphere of 5% H_2-95% N_2 slightly reduced tensile strength and toughness: from 748 to 734 MPa and from 7.15 to 6.83 J/cm^2, respectively. Chemical composition had a greater effect; steels based on Astaloy CrL and Astaloy CrM had tensile strengths 526-665 and 672-748 MPa, hardness 280-325 and 388-421 HV, respectively. The best properties were obtained after sintering in air of Fe-3%Mn-3%Cr-0.5%Mo-0.2%C without heat treatment: tensile strength 672 MPa, toughness 6.93 J/cm^2, hardness 421.1 HV, 0.2 % offset yield strength 395 MPa.

Keywords: PM steel, microstructure, mechanical properties

1. Introduction

In Powder Metallurgy the common alloying elements for producing high-strength structural steels are nickel and copper. Nickel has a positive effect on mechanical properties of steel, but it is expensive and injurious to health. European Union Directives [1,2] required a recall of nickel as an alloying element in steels because of its carcinogenic character. Studies have shown that a good substitute of nickel in sintered steels is manganese. In the phase equilibrium diagram Fe-Mn-C at 1100°C (Fig. 1) three phases: austenite, ε phase and cementite (with a higher content of manganese than solid solution) are present. In this system austenite is a stable phase with low carbon content. To stabilize the austenite higher content of manganese is needed [3]. Manganese is cheap and easily accessible, steels with this element have similar properties to PM Ni steels. On the other hand, manganese has a high affinity for oxygen and creates problems during production, so this element is added to powder mixtures as a ferroalloy. It is important to select carefully the sintering atmosphere because manganese can easily form oxides. PM Mn steels were sintered in hydrogen and mixture hydrogen-nitrogen [4]. Results of investigations reported in papers [5-9] are promising.

Chromium forms unstable carbides in steel. However this element is cheap and common. It increases corrosion resistance, especially to intercrystalline corrosion. It can also delay transformation during tempering [10]. Molybdenum is often used for nitriding, because it forms nitrides which strengthen steel. This element increases hardenability and creep resistance [10]. It narrows the area of the prevalence of austenite. Steel consisting of 3% of molybdenum has a ferritic structure. Molybdenum has a high affinity for carbon and forms carbides, for example Mo_6C.

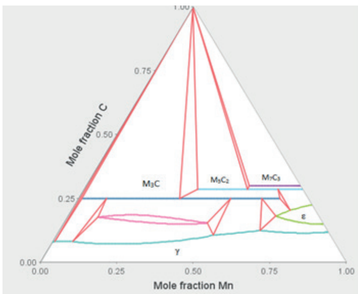

Fig. 1. The isopleth section of phase equilibrium diagram of PM Fe-Mn-C steels at 1100°C

In Fig. 2 phase equilibrium diagrams of two different steels: 3% Mn, 1.5 % Cr and 0.2 % Mo (Fig 2a), 3 % Mn, 3 % Cr and 0.5 % Mo (Fig 2b) based on different concentrations of carbon are presented. The eutectic is moving to lower concentration of carbon when the amount of alloying elements is higher (3% Cr, 0.5% Mo). PM steels with lower amounts of alloying elements are characterized by less stable phases, for example ferrite.

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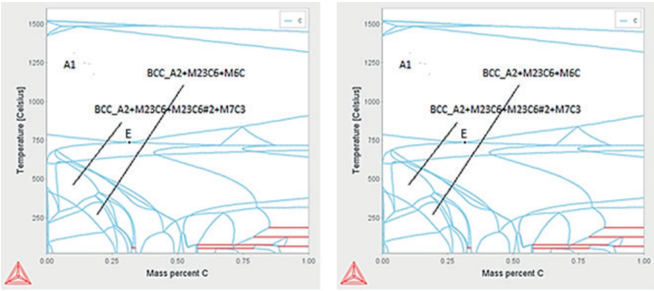


a) b)

Fig. 2. The isopleth section of phase equilibrium diagram of steel with a) – 3% Mn, 1.5% Cr, 0.2% Mo, b) – 3% Mn, 3% Cr, 0.5% Mo, with selected phases [13]

So far, sintered structural steels were produced in atmospheres with high content of hydrogen. However this atmosphere is explosive and expensive. Investigations of Mn and Mn-Cr-Mo steels sintered in nitrogen with a low content of hydrogen provide similar or higher mechanical properties than steels sintered in hydrogen [7, 9]. In the project [11] promising results of sintering Mn-Cr-Mo steels in air are presented. The change of atmosphere composition would make it possible to reduce costs of industrial production of sintered structural PM steels.

The aim of this paper is to specify the influence of production parameters, especially chemical composition of sintering atmosphere and heat treatment, on the mechanical properties of Fe-3%Mn-1.5%Cr-0.2%Mo-0.2%C and Fe-3%Mn-3%Cr-0.5%Mo-0.2%C sintered steels.

2. Experimental procedures

The following base powders were used:

- pre-alloyed iron-powders (produced by Höganäs),
  - Astaloy CrL consists of 1.5 % Cr, 0.2 % Mo, 98.25 % Fe,
  - Astaloy CrM consists of 3 % Cr, 0.5 % Mo, 96.5 % Fe,
- low-carbon ferromanganese (77 % Mn, 1.3 % C) produced by Eramet Comilog Manganese,
- graphite powder C-UF (produced by Höganäs),

From base powders, using a Turbula mixer for 30 minutes, powder mixtures with compositions: Fe-3 % Mn-1.5 Cr-0.2 % Mo-0.2 % C and Fe- 3% Mn-3 % Cr-0.5 % Mo-0.2 % C were prepared. The technological properties of the powders were described in papers [4, 5].

From powder mixtures, using single-action pressing in rigid dies, two types of samples were prepared: rectangular 5 x 10 x 55 mm and tensile test bars according to ISO PN-EN 2740 standard. Pressing pressure were 820 MPa and 660 MPa, respectively.

Following pressing, sintering was carried out at 1250°C for 60 minutes using hydrogen-nitrogen atmosphere with H_2-N_2 ratio=5-95%. Heating and cooling rates were 75°C/min. and 65°C/min., respectively. Sintering was also carried out in a semi-closed container in air. During sintering in air lumps of FeMn were added into the container. After sintering, half of the samples was tempered at 200°C for 60 minutes in air.

Green and as-sintered (as-tempered) densities were calculated by the geometrical method. Tensile and bend strength, toughness and hardness were calculated, with UTS according to 10002-1 standard. During tensile test the cross-head speed was 1 mm/min. TRS was measured following PN-EN 3325 standard on test samples parallel to the pressing direction. The load was applied to the surface on which the pressing punch was contacted. The investigation of toughness of samples was carried out according to PN-EN ISO 25754 and PN-EN ISO 10045-1 standards. Charpy test machine with energy of 15 J was used. The investigation of apparent and cross-sectional hardness was carried out using the Vickers method according to a PN-EN ISO 3870 standard on rectangular samples, according to the procedure described in [12].Metallographic examinations were made using Leica DM4000M optical microscope in bright field with magnification of 500x. Samples were prepared according to the procedure described in paper [12].

3. Results

Following the results of pressing and sintering received compacts and as-sintered with similar densities are summarized in Table 1.

TABLE 1

The densities of the steels – mean values and standard deviations

Rectangular samples		Green density compacts, d_o, g/cm^3	As-sintered density, d_s, g/cm^3
Fe-3Mn-1.5Cr-0.2Mo-0.2C	mean values	7.06	7.07
	stand. dev.	0.07	0.05
Fe-3Mn-3Cr-0.5Mo-0.2C	mean values	6.98	7.00
	stand. dev.	0.05	0.06
ISO samples		Green density compacts, d_o, g/cm^3	As-sintered density, d_s, g/cm^3
Fe-3Mn-1.5Cr-0.2Mo-0.2C	mean values	6.62	6.62
	stand. dev.	0.03	0.03
Fe-3Mn-3Cr-0.5Mo-0.2C	mean values	6.61	6.60
	stand. dev.	0.06	0.03

Tables 2 and 3 present the mechanical properties (mean values and standard deviations). In Figures 3 and 4 cross section hardness profile of Fe-3Mn-1.5Cr-0.2Mo-0.2C and Fe-3Mn-3Cr-0.5Mo-0.2C PM steels sintered in $5H_2 95N_2$% atmosphere with tempering and without heat treatment are presented. Figures 5-8 show the microstructures.

TABLE 2

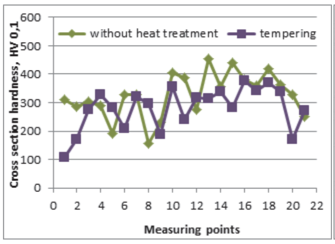
Mechanical properties of the PM steels based on Astaloy CrL powder – mean values and standard deviations

Fe-3% Mn-1.5% Cr-0.2% Mo-0.2% C						
Temperature, °C and sintering atmosphere	UTS [MPa]	A [%]	$R_{0,2}$ [MPa]	KC [J/cm²]	TRS [MPa]	HV 0.1 (cross section)
1250°C/5%H_2-95%N_2/not tempered	665	2.77	345	10.56	1289	325.8
	±68	±0.45	±20	±1.02	±151	±76.2
1250°C/5%H_2-95%N_2/tempering 200°C/air/ 60 min.	608	2.25	386	8.83	1275	280.9
	±75	±0.50	±24	±1.14	±130	±73.0
1250ºC/air/not tempered	612	2.15	353	8.49	1205	306.6
	±50	±0.34	±20	±0.87	±101	±87.7
1250°C/air/tempering 200°C/air/60 min.	526	1.65	384	7.36	1237	315.3
	±106	±0.52	±35	±1.23	±99	±90.0

TABLE 3

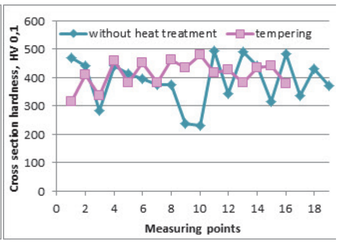
Mechanical properties of the PM steels based on Astaloy CrM powder – mean values and standard deviations

Fe-3% Mn-3% Cr-0.5% Mo-0.2% C						
Temperature, °C and sintering atmosphere	UTS [MPa]	A [%]	$R_{0,2}$ [MPa]	KC [J/cm²]	TRS [MPa]	HV 0.1 (cross section)
1250°C/5%H_2-95%N_2 not tempered	748	2.98	403	7.15	1189	388.4
	±106	±0.70	±11	±1.73	±201	±79.8
1250°C/5%H_2-95%N_2 tempering 200°C/air/60 min.	734	2.51	470	6.86	1326	412.5
	±42	±0.37	±17	±0.72	±145	±45.2
1250ºC/air not tempered	672	2.66	395	6.93	1224	421.1
	±88	±0.96	±48	±1.64	±147	±54.2
1250°C/air tempering 200°C/air/60 min.	679	2.51	459	6.03	1093	405.8
	±37	±0.58	±38	±1.05	±144	±59.4



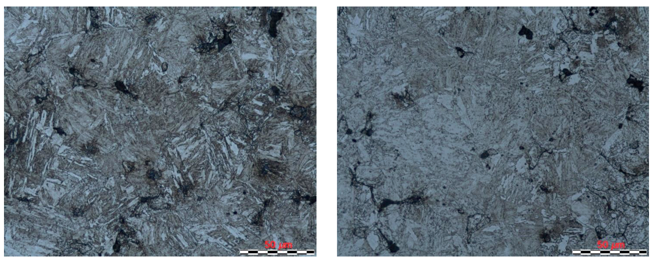
a

Fig. 3. Cross section hardness of Fe-3Mn-1.5Cr-0.2Mo-0.2C PM steel sintered in 5H_2-95N_2 atmosphere



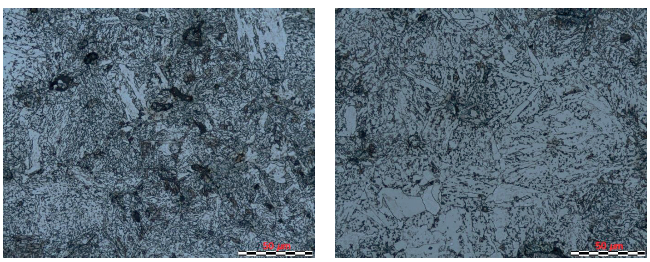
b

Fig. 4. Cross section hardness of Fe-3Mn-3Cr-0.5Mo-0.2C PM steel sintered in 5H_2-95N_2 atmosphere



a b

Fig. 6. The microstructure of Fe-3Mn-1.5Cr-0.2Mo-0.2C steel sintered in air a – without heat treatment – ferrite, bainite; b – after tempering at 200°C for 60 minutes in air – ferrite, bainite



a b

Fig. 5. The microstructure of Fe-3Mn-1.5Cr-0.2Mo-0.2C steel sintered in 5H_2-95N_2 atmosphere a – without heat treatment – ferrite, bainite; b – after tempering at 200°C for 60 minutes in air – ferrite, bainite

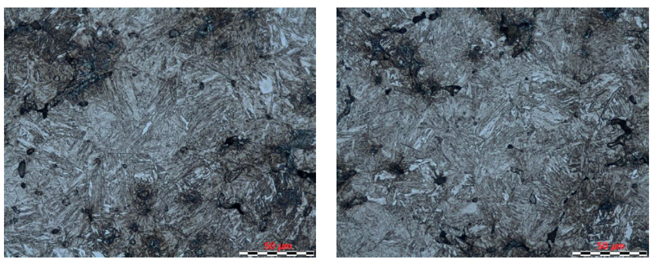


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Fig. 7. The microstructure of Fe-3Mn-3Cr-0.5Mo-0.2C steel sintered in 5H_2-95N_2 atmosphere a – without heat treatment – ferrite, bainite, pearlite; b – after tempering at 200°C for 60 minutes in air – ferrite, bainite, pearlite

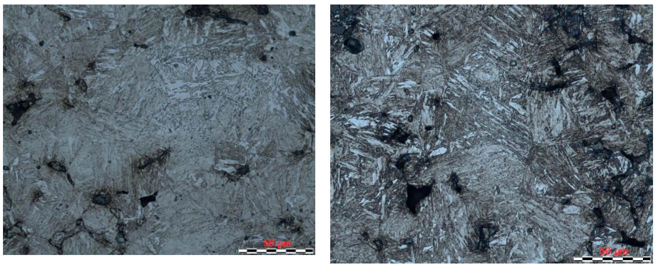

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Fig. 8. The microstructure of Fe-3Mn-3Cr-0.5Mo-0.2C steel sintered in air a – without heat treatment – ferrite, bainite, pearlite; b – after tempering at 200°C for 60 minutes in air – ferrite, bainite, pearlite

4. Discussion

Chemical composition has the essential influence on mechanical properties and the structure of investigated PM steels. Increasing the content of chromium and molybdenum from 1.5% to 3% and from 0.2% to 0.5% respectively, increased tensile strength and hardness. Increased content of alloying elements decreased the temperature of pearlitic and bainitic transformations. Mo and Cr are carbide forming elements, so their higher content strengthens the steel by forming more dispersed carbides.

Atmosphere had slight influence on properties: tensile strength and toughness decreased slightly after sintering in air. This may involve a slight decarburization of as-sintered materials.

Properties of steel after tempering depend on concentration of alloying elements and temperature of heat-treatment. Tempering had a small effect on improving the mechanical properties of samples. After tempering the yield strength increased. This may indicate the presence of strengthening carbides inside the ferrite [14].

Increased brittleness after tempering is evidenced by the lower toughness and A [%]. There was also less scatter in the microhardness of tested steels after heat treatment (Fig. 3-4). This maydue to reduced heterogeneity of heat-treated steels in comparison with steels without heat-treatment.

Ferrite and bainite in microstructure of Fe-3%Mn-1.5%Cr-0.2%Mo-0.2%C sintered in hydrogen-nitrogen were observed, which correlates with results presented in papers [13, 15-21]. Lower bainite is ferrite supersaturated with carbon with lamellar structure, which inside of grains has finely dispersed carbides [10]. After sintering in air the amount of ferrite increased and amount of bainite decreased, which correlates with results presented in paper [17]. This may involve a slight decarburization of as-sintered materials, which correlates with hardness values in Tables 2 and 3. The microstructures of Fe-3%Mn-3%Cr-0.5%Mo-0.2%C were inhomogeneous ferritic-bainitic-pearlitic. The presence of bainite (Fig. 5-8) influences hardness and plasticity - about 2.5% (Tables 2 and 3) [19-21].

After sintering at 1250°C the investigated steels had higher densities than steels sintered at 1120°C. Increased density caused improvement of mechanical properties: UTS from 550 to 650 MPa, A from 2 to 2.5%, R0.2 from 350 to 450 MPa, toughness from 6 to 8 J/cm^2 [11].

The best properties were obtained by sintering in air at 1250°C of Fe-3%Mn-3%Cr-0.5%Mo-0.2%C without heat treatment: tensile strength 672 MPa, toughness 6.93 J/cm^2, hardness 421.1 HV, 0.2 %, offset yield strength 395 MPa.

5. Conclusions

Tempering of the steels sintered in atmospheres of 5%H_2-95%N_2 and air slightly lowers tensile strength and toughness.

Chemical composition has the essential influence on mechanical properties and structure of the investigated PM steels.

The best properties of steel with a composition of Fe-3% Mn-3% Cr-0.5% Mo-0.2% C were obtained after sintering at 1250°C in air in a semi-closed container without additional heat treatment.

Steels sintered at 1250°C are characterized by good mechanical properties.

Investigated steels have a ferritic-bainitic and ferritic-bainitic-pearlitic structures.

After sintering in air in a semi-closed container a slight decarburization of investigated PM steels occurred.

Sintering in air, in semi-closed container, of steels based on Astaloy CrM with addition of Mn is a good alternative to sintering of these steels in an expensive hydrogen atmosphere.

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